

ON THE DISTRIBUTION OF X-RAY SURFACE BRIGHTNESS FROM DIFFUSE GAS

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ABSTRACT

Hot intergalactic gas in clusters, groups, and filaments emanates a continuous background of 0.5–2.0 keV X-rays that ought to be detectable with the new generation of X-ray observatories. Here we present selected results from a program to simulate the surface-brightness distribution of this background with an adaptive-mesh cosmological hydrodynamics code. We show that the bright end of this distribution is well approximated by combining the cluster temperature function with a β -model for surface brightness and appropriate luminosity-temperature and core radius-luminosity relations. Our simulations verify that the X-ray background from hot gas vastly exceeds observational limits if non-gravitational processes do not modify the intergalactic entropy distribution. An entropy floor $\sim 100 \text{ keV cm}^2$, which could be established by either heating or cooling, appears necessary to reconcile the simulated background with observations. Because the X-ray background distribution is so sensitive to the effects of non-gravitational processes, it offers a way to constrain the thermal history of the intergalactic medium that is independent of the uncertainties associated with surveys of clusters and groups.

Subject headings: cosmology: diffuse radiation — intergalactic medium — X-rays: general

1. INTRODUCTION

Beneath the scattered point sources that speckle the X-ray sky should lie a subtler, more continuous background of X-rays emanating from the hot gas that fills the spaces between galaxies. Many, if not most, of the universe's baryons inhabit intergalactic space and are heated to temperatures of $10^5 - 10^7 \text{ K}$ by gravitationally-driven shocks (e.g., Cen & Ostriker 1999; Davé et al. 2000). Once heated, these baryons tend to settle into gravitational potential wells and assume the characteristic temperature of the dark matter that confines them. Because the emissivity of these baryons depends on how severely they are compressed, the mean intensity of the continuous X-ray background reflects the amount of non-gravitational energy injected into intergalactic space. Large amounts of energy injection by supernovae and active galactic nuclei can inhibit compression of the intergalactic medium, lowering the mean level of the continuous background.

Current estimates place the point-source contribution to the 0.5–2 keV background at $\gtrsim 80\%$ (Hasinger et al. 1998; Mushotzky et al. 2000; Giacconi et al. 2000), meaning that hot intergalactic gas contributes less than 20%, which amounts to $\lesssim 5 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$. A sizeable fraction of this residual emission comes from clusters of galaxies. Integrating over the observed luminosity function of clusters, assuming no luminosity evolution, places the background from clusters hotter than 5 keV at $\sim 2.5 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$. However, these clusters cover only $\sim 1\%$ of the sky. The remainder is covered by a confused patchwork of groups and intercluster filaments whose properties depend critically on non-gravitational processes. If gravitational processes alone were responsible for establishing the entropy distribution of intergalactic gas, emission from groups and fila-

ments would vastly overproduce the remainder of the 0.5–2 keV background (Pen 1999; Wu, Fabian, & Nulsen 2000). Somehow, the lowest-entropy, most compressible gas has been eliminated. Non-gravitational heating has been the most widely studied way of establishing this entropy floor, but it is also possible that low-entropy gas has been removed by radiative cooling and subsequent condensation (e.g., Bryan 2000).

Analyzing individual groups and filaments to determine the impact of energy injection and cooling will not be easy. Several factors complicate the task of compiling unbiased samples of X-ray emitting groups: Groups are low surface-brightness objects, some apparent groups are chance superpositions of galaxies, and the potential wells of individual galaxies can strongly affect a group's X-ray properties (see Mulchaey 2000 for a review). Projection effects further complicate matters. Virialized objects with $kT > 0.5 \text{ keV}$ cover over a third of the sky, making individual filaments very difficult to isolate and creating a significant probability that one group will overlap another somewhere along the same line of sight (Voit, Evrard, & Bryan 2000). For example, about three higher-redshift $> 0.5 \text{ keV}$ groups are expected to lie within the projected virial radius of a 0.5 keV group at $z \approx 0.1$.

Because of these projection effects, statistical analyses of the 0.5–2 keV surface brightness distribution should be explored as an alternative way to characterize the lowest surface-brightness structures in the X-ray sky and perhaps to gauge the impact of non-gravitational energy injection and cooling. We have begun to investigate this brightness distribution using both hydrodynamical simulations and semi-analytical techniques and report some of our early results in this letter. Section 2 briefly describes our simulations of the X-ray surface brightness distribution and shows how the high-brightness end can be approximated

with a semi-analytical model. Section 3 demonstrates that non-gravitational processes strongly influence this distribution function, and § 4 summarizes our results.

2. SIMULATED SURFACE-BRIGHTNESS DISTRIBUTIONS

Our analysis of the X-ray background owing to intergalactic gas centers on the quantity $P(S)$, the probability that a given line of sight through the universe will have a 0.5-2 keV surface brightness $> S$. The ideal computation of $P(S)$ would involve a hydrodynamical simulation encompassing the entire observable universe, but this is currently infeasible. Instead, we have chosen to simulate a box large enough to contain a fair sample of clusters and groups, yet small enough to resolve the cores of these virialized objects. A companion paper (Bryan & Voit 2001) describes in more detail these simulations, which employ an adaptive mesh refinement technique for the hydrodynamics (Bryan 1999; Bryan & Norman 1997; Norman & Bryan 1999). Here we will focus on simulations of a $50 h^{-1}$ Mpc box with 128^3 grid points and mesh refinement down to a minimum cell size of $24 h^{-1}$ kpc.

We reconstruct $P(S)$ for lines of sight from $z = 0-10$ by computing dP/dS for the box alone at a number of discrete redshift points to determine how dP/dS varies with redshift for a given comoving box size. At any given redshift, the comoving size of our simulation box corresponds to a redshift interval Δz , so we can reconstruct dP/dS for the entire line of sight by appropriately convolving the individual distributions corresponding to each redshift interval (see Bryan & Voit 2001 for more details). This procedure yields the distribution shown in Figure 1 for a Λ CDM cosmology ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 0.9$) with a baryon fraction $\Omega_b = 0.04$ and without non-gravitational energy injection. Because of the limited box size, we cannot capture brightness enhancements owing to correlated structure on $> 50 h^{-1}$ Mpc scales, but we anticipate that their effect on $P(S)$ will be small.

Several features of this distribution are worth noting. First, the mean surface brightness is $\bar{S} = 2.5 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$, about five times higher than allowed by observations, verifying the expectations of Pen (1999) and Wu et al. (2000). In addition, our numerical experiments reveal that \bar{S} depends on numerical resolution, implying that \bar{S} in an optimally resolved simulation would be even higher (Bryan & Voit 2001). Second, $P(S) \approx 0.5$ at $S \sim 5 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$ indicating that the median value of S is close to the maximum allowed by observations. Third, the quantity $S|dP/dS|$ shows a broad peak between 10^{-16} and $10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$, indicating that most lines of sight have a surface brightness broadly distributed in this range. Finally, we show for comparison two $P(S)$ distributions derived from the power-law fits to ROSAT and Chandra point-source counts of Hasinger et al. (1998) and Giacconi et al. (2000) assuming Gaussian point-spread functions with full-width at half-max of 1 arcsec and 10 arcsec. In both cases, diffuse hot gas dominates the surface-brightness distribution from 10^{-16} to $10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$.

An early hydrodynamical computation of X-ray surface brightness was performed by Scaramella, Cen, & Ostriker (1993), who computed the mean and variance of the specific intensity at 1 and 2 keV for a standard

CDM cosmology using simulations of somewhat lower effective resolution. Because of the different cosmological model and resolution limit, their results are difficult to compare directly with our own. However, we do verify their conclusions regarding the brightness distribution at intermediate brightness levels. Scaramella et al. (1993) found that the pixel distribution of specific intensity (I_X) varies like $I_X^{-1.76}$, equivalent to $P(S) \propto S^{-0.76}$. Figure 1 illustrates this power-law slope, which is quite similar to that of our model in the neighborhood of 10^{-14} to $10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$.

This scaling stems from the β -model surface brightness distribution typical of clusters of galaxies. Most clusters are adequately fit by the law $S \propto [1 + (r/r_c)^2]^{-3\beta+1/2}$, where r_c is the cluster's core radius. (Cavaliere & Fusco-Femiano 1978). For an individual cluster we therefore have $P \propto S^{[2/(1-6\beta)]}$, which reduces to $P \propto S^{-2/3}$ for $\beta = 2/3$, quite close to the slope found by Scaramella et al. (1993). As Figure 1 shows, this relation is also a good approximation of $P(S)$ in the intermediate range.

Because the simulations produce clusters and groups that are well fit by β -models, we can successfully reproduce our simulated $P(S)$ through semi-analytical means. Following Voit et al. (2000), we have taken the cluster catalog from the Λ CDM Hubble Volume simulation performed by the Virgo Consortium (Evrard 1999; Macfarland et al. 1998; Frenk et al. 2000) and have computed $P(S)$ assuming $\beta = 2/3$ surface-brightness profiles and the core radius-luminosity relation from Jones et al. (1998). However, instead of using the observed L_X - T relation, we assume $L_{\text{bol}} \propto T^2$, correct L_X to the 0.5-2.0 keV band as described in Bryan & Norman (1998) for a metallicity of 0.3 solar, and normalize the relation to fit our simulated clusters at ~ 1 keV. Figure 2 compares the resulting $P(S)$ distribution with the hydrodynamical model and the $P(S)$ derived from the Hubble Volume catalog using the ROSAT L_X - T relation observed by Markevitch (1998) instead of the one derived from the simulation.

Apparently, the contribution to $P(S)$ from the virialized regions of clusters and groups can be adequately modeled by combining the cluster mass function with appropriate analytical equations relating luminosity to mass and to a cluster's surface-brightness profile. The excellent agreement between the simulated and semi-analytical $P(S)$ distributions also simplifies the task of identifying the major contributors at each level of S . The steep slope of $P(S)$ at the surface-brightness levels of cluster cores ($\sim 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$) echoes the steep slope of the cluster mass function. Between $10^{-15} \lesssim S \lesssim 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$ the β -model outskirts of clusters and groups dominate the background, and below $10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$ is the realm of true intercluster emission.

3. THE SIGNATURE OF NON-GRAVITATIONAL PROCESSES

Our model without energy injection is illuminating but clearly does not represent reality, primarily because \bar{S} is far too high. Applying the observed L_X - T relation to the Hubble Volume clusters significantly shifts the $P(S)$ distribution to lower S (see Figure 2) with $\bar{S} \approx 6 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$, on the verge of being disallowed by observations. However, this model relies on an

uncertain extrapolation of the cluster L_X - T relation down to group scales. In fact, the L_X - T relation may steepen below ~ 1 keV, perhaps because supernova energy injection becomes comparable to the gravitational energy of the intragroup gas (e.g., Heldson & Ponman 2000).

In order to explore the effect of non-gravitational energy injection on $P(S)$, we have run a hydrodynamical model with a very simple prescription for preheating: we instantaneously add 1.5 keV of energy per baryon at $z = 3$, similar to the level needed to explain the observed L_X - T relation for clusters (e.g., Ponman, Cannon, & Navarro 1999). Figure 3 shows the resulting $P(S)$ in terms of the quantity $S^2|dP/dS|$, which peaks in the neighborhood of S values that contribute most to the mean. The distribution has indeed shifted to lower S , relative to the no-preheating case, and $S^2|dP/dS|$ has also flattened, indicating that a larger range of S contributes significantly to the mean. Yet, the mean surface brightness, $\bar{S} = 6.8 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$, still exceeds observational limits. Furthermore, our numerical experiments indicate that even this value may be an underestimate (Bryan & Voit 2001).

Another crude but inexpensive way to explore the effects of non-gravitational processes is to apply an ad hoc entropy floor to the simulation results. The heat input required to explain the scaling properties of clusters corresponds to a minimum entropy level $(Tn^{-2/3})_{\min} \sim 100 \text{ keV cm}^2$ (e.g., Ponman et al. 1999). Interestingly, the same critical entropy level also emerges from cooling considerations: ~ 1 keV gas will cool and condense within a Hubble time if its specific entropy level is $\lesssim 100 \text{ keV cm}^2$. In either case, establishing an entropy floor lowers the mean gas density in the cores of groups and clusters. Thus, we have chosen to mimic the effect of an entropy floor by recalculating $P(S)$ after substituting the quantity $[n^{-2/3} + (Tn^{-2/3})_{\min}/T]^{-3/2}$ for the original gas density. Figure 3 shows the resulting $S^2|dP/dS|$ distributions. For $(Tn^{-2/3})_{\min} = 100 \text{ keV cm}^2$, we obtain $\bar{S} \approx 4.6 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$, just barely consistent with current observations, and for $(Tn^{-2/3})_{\min} = 200 \text{ keV cm}^2$, we obtain $\bar{S} \approx 3.1 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$.

Croft et al. (2000) have recently performed a similar computation using a smooth-particle hydrodynamics code that includes cooling and a prescription for supernova feedback and find $\bar{S} = 6.4 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$.¹ Because the simulation analyzed by Croft et al. includes multiple non-gravitational processes that ours do not, it is

difficult to pinpoint the process most responsible for lowering their value of \bar{S} . Quite possibly, removal of low-entropy gas by cooling and condensation could be just as important as supernova heating in establishing \bar{S} and the L_X - T relation of groups and clusters (see also Bryan 2000). It also remains possible that \bar{S} would be larger in a higher-resolution SPH computation. Additional simulations will be needed to clarify the roles of various non-gravitational processes and to relate the thermal history of intergalactic baryons to the $P(S)$ distribution.

Given the difficulties in compiling an unbiased L_X - T relation for groups, we suggest that observations of the $P(S)$ distribution at 0.5-2 keV be pursued as an alternative way to constrain preheating and radiative cooling. The quantity $S^2|dP/dS|$ is clearly sensitive to non-gravitational processes like energy injection and cooling, particularly around $S \sim 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$, and the background from hot gas is competitive with the point-source background in *Chandra* and *XMM-Newton* observations over the interesting range of S ($10^{-13} - 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$). Identification of extended sources and follow-up redshift surveys are unnecessary. However, the trick will be to distinguish the true astronomical background from non-astronomical detector events.

4. SUMMARY

We have derived the 0.5-2 keV surface-brightness distribution function $P(S)$ from hydrodynamical simulations of structure formation in a Λ CDM cosmology. The bright end of this distribution is well reproduced by combining the cluster catalog from the Λ CDM Hubble Volume simulation with appropriate L_X - T and r_c - L_X relations and a $\beta = 2/3$ surface-brightness law. Without non-gravitational heating or cooling, \bar{S} exceeds observed limits by a factor of several. Another simulation that adds ~ 1 keV of energy at $z = 3$ substantially lowers \bar{S} , but not by enough. An entropy floor $\sim 100 \text{ keV cm}^2$ appears necessary to reconcile our simulations with observational limits. Observations of $P(S)$ with *Chandra* and *XMM-Newton* appear to be a promising way to constrain the thermodynamical history of this intergalactic gas.

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¹After our letter was submitted, Phillips et al. (2000) announced X-ray brightness results from an Eulerian hydrodynamical computation that includes cooling and feedback in a Λ CDM cosmology with $\Omega_b = 0.035$. Their value for the 0.5 - 2 keV background from diffuse gas, $\bar{S} = 1.8 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$, is even lower, partly because of the lower baryon fraction.

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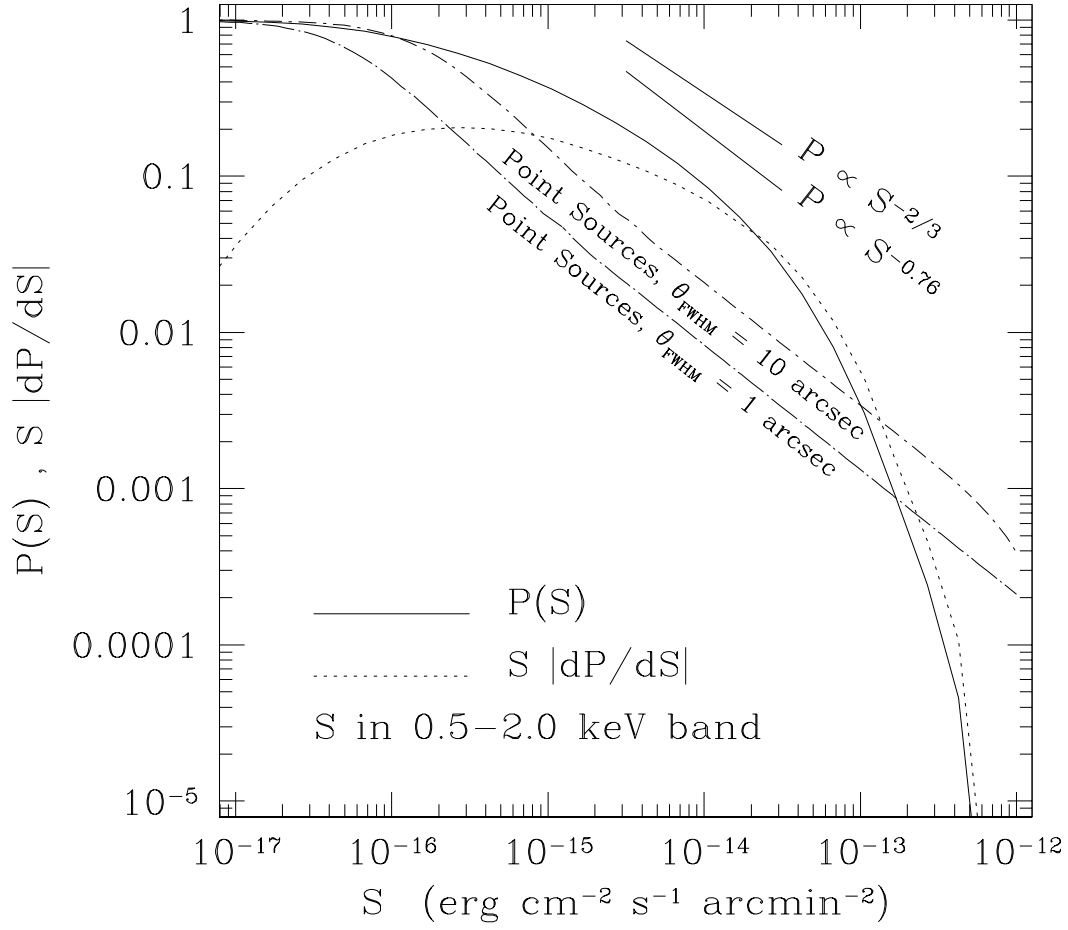


FIG. 1.— Probability $P(S)$ of observing a 0.5–2.0 keV surface brightness $> S$ along a given line of sight. The solid line shows $P(S)$ for hot intergalactic gas derived from a hydrodynamic simulation. The dotted line shows the corresponding differential distribution $S|dP/dS|$. The other two lines show $P(S)$ owing to point sources for two different Gaussian point-spread functions, one with a full-width at half-max of 10 arcsec, the other with FWHM of 1 arcsec.

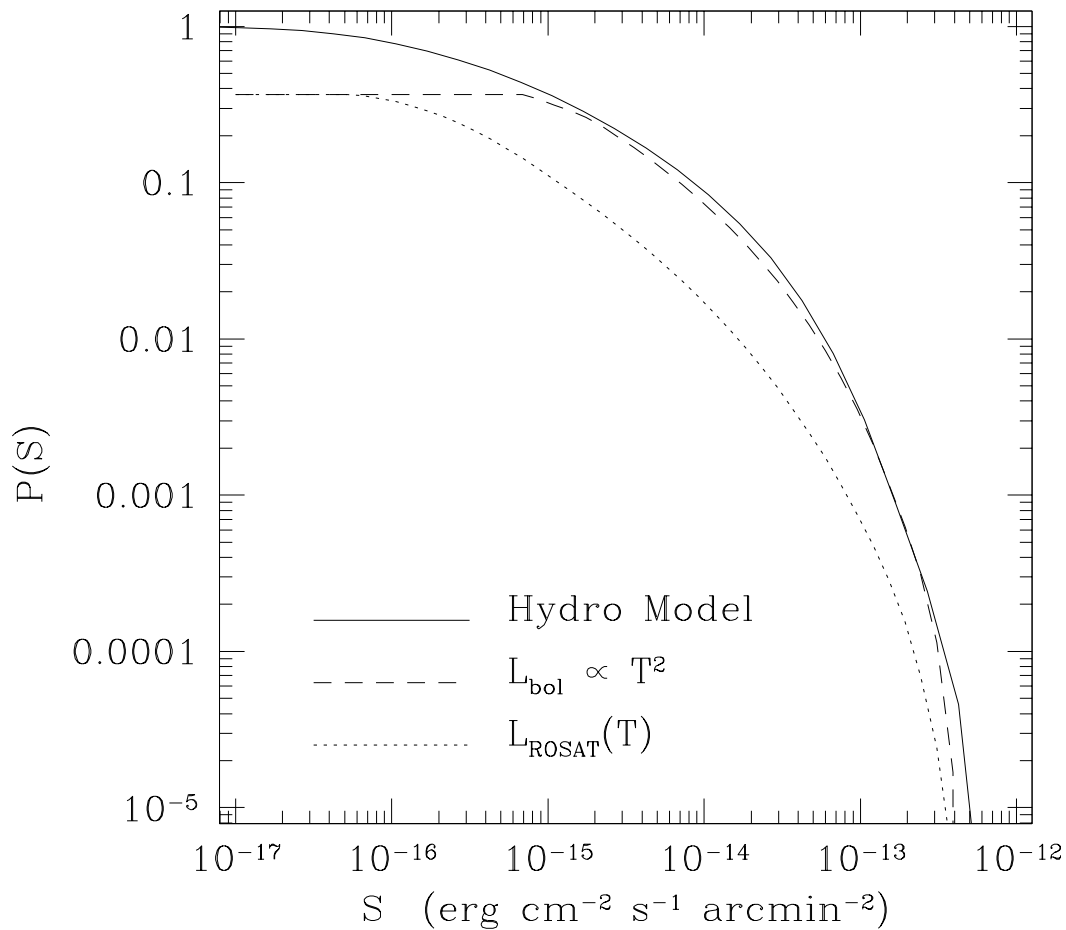


FIG. 2.— Comparison of surface-brightness distributions from hydrodynamical models and semi-analytical methods. Above brightness levels of $10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$ the $P(S)$ from our hydrodynamical model with no preheating (solid line) is closely approximated by the $P(S)$ derived from the Λ CDM Hubble-Volume simulation (dashed line) using a luminosity-temperature relation with $L_{\text{bol}} \propto T^2$ and β -model surface-brightness profiles with the luminosity-core radius relation of Jones et al. (1998). Applying the *ROSAT* L_X - T relation observed by Markevitch (1998) to the Λ CDM Hubble-Volume simulation (dotted line) leads to a somewhat lower $P(S)$ distribution more consistent with current observational limits on \bar{S} .

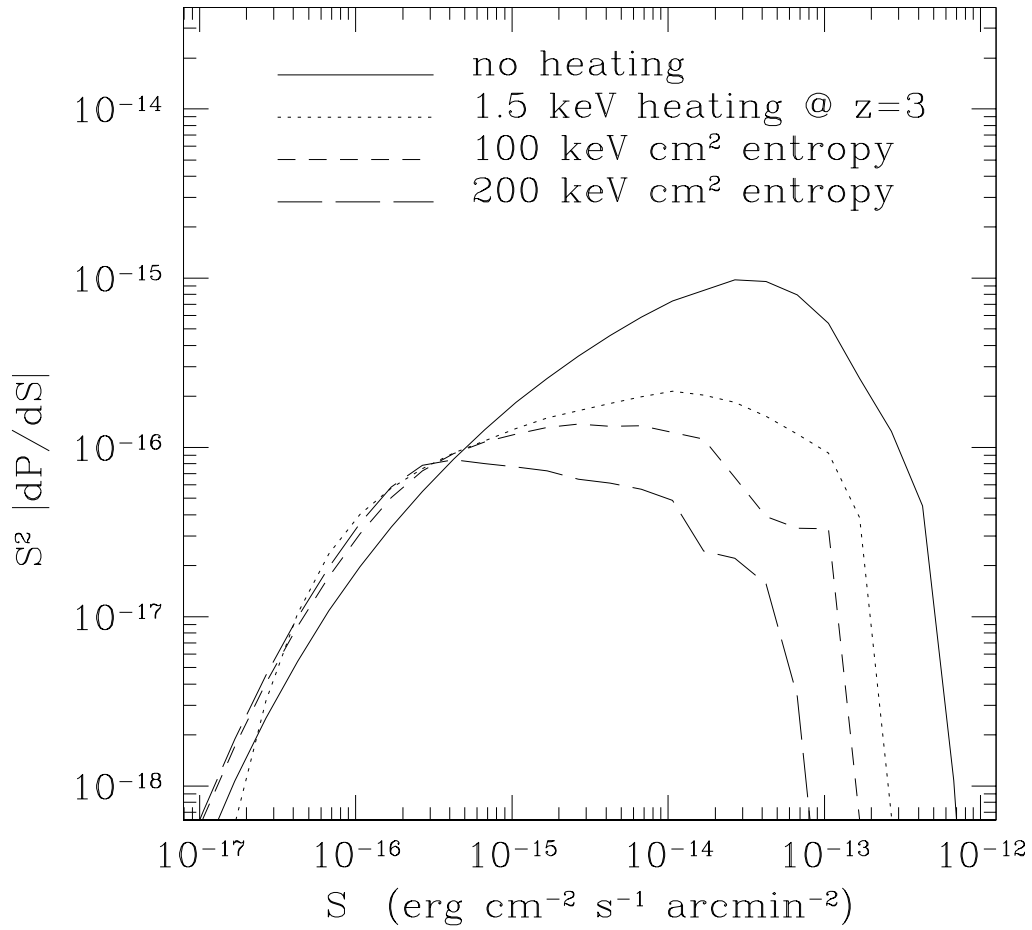


FIG. 3.— Comparison of $S^2|dP/dS|$ with various treatments of non-gravitational processes. The quantity $S^2|dP/dS|$ peaks at the surface-brightness levels that contribute most to the mean. Without preheating or radiative cooling (solid line), $S^2|dP/dS|$ peaks at brightness levels typical of the cores of groups and clusters. Adding energy equivalent to 1.5 keV of energy per particle at $z = 3$ (dotted line) dramatically flattens $S^2|dP/dS|$ and shifts it to lower S . Applying an entropy floor to the simulation results (see text for details) has a similar effect. Thus, observations of $S^2|dP/dS|$ between 10^{-15} and 10^{-13} $\text{erg cm}^{-2} \text{s}^{-1} \text{arcmin}^{-2}$ are potentially very sensitive to the effects of non-gravitational processes.